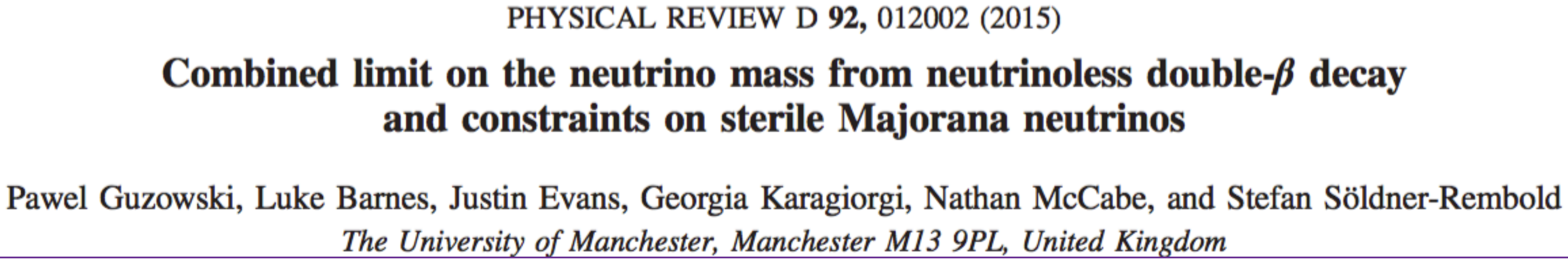
A combined limit for neutrinoless double-beta decay

Pawel Guzowski



PHYSICAL REVIEW D **92,** 012002 (2015)

Combined limit on the neutrino mass from neutrinoless double-β decay and constraints on sterile Majorana neutrinos

Pawel Guzowski, Luke Barnes, Justin Evans, Georgia Karagiorgi, Nathan McCabe, and Stefan Söldner-Rembold
The University of Manchester, Manchester M13 9PL, United Kingdom

The University of Manchester

Outline

- Combined limit from 6 experimental inputs:
    - CUORICINO and CUORE-0
    - EXO-200
    - GERDA
    - KAMLAND-Zen
    - NEMO-3
- Cross-check of these individual results
- The combination
    - Nuclear Matrix Element model dependence
- Limits on sterile Majorana neutrinos

Introduction

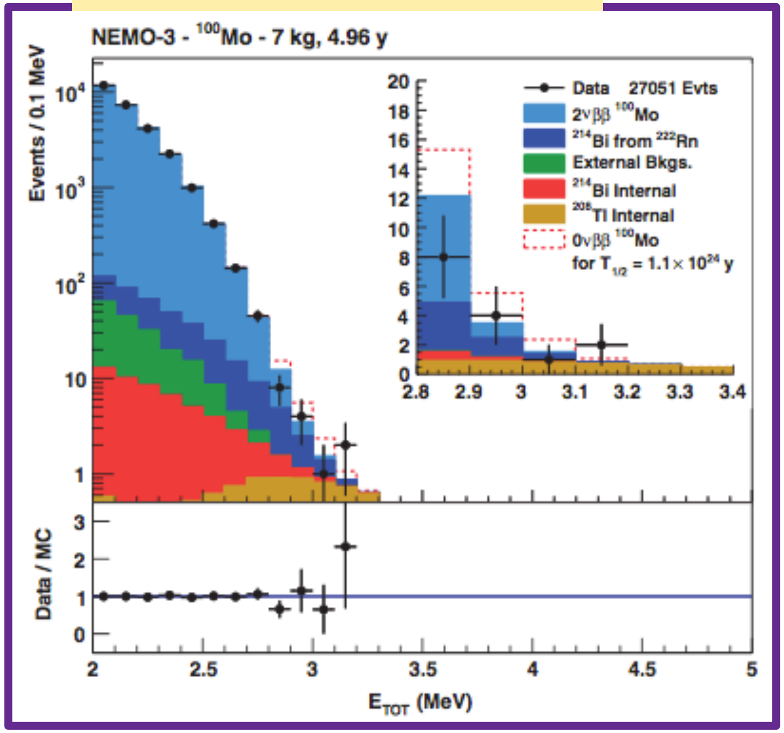
- Limits on 0$\nu\beta\beta$ have only so far been set for single experiments, or for a single isotope
- Combining results for multiple isotope is important, for improving sensitivity, and also for disentangling mechanisms if an observation is made
- We introduce a method for combining results of different experiments, and apply it to 6 recent experimental results
  - COURICINO/CUORE-0, EXO-200, GERDA, KamLAND-Zen & NEMO-3

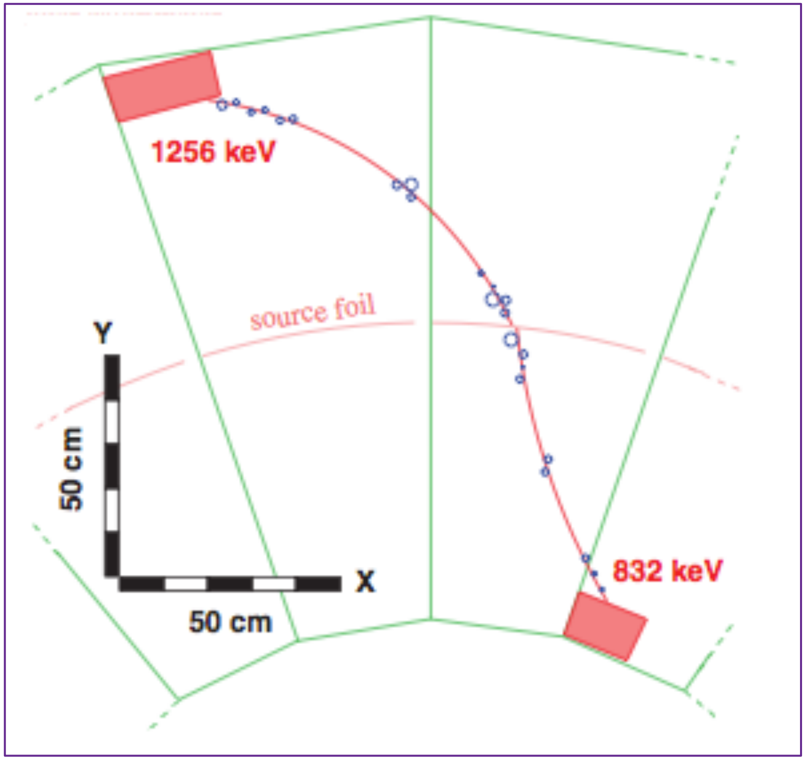
THE EXPERIMENTS

NEMO-3

- Tracker-calorimeter
  - ^{100}Mo isotope

PRD 89, 111101 (2014)



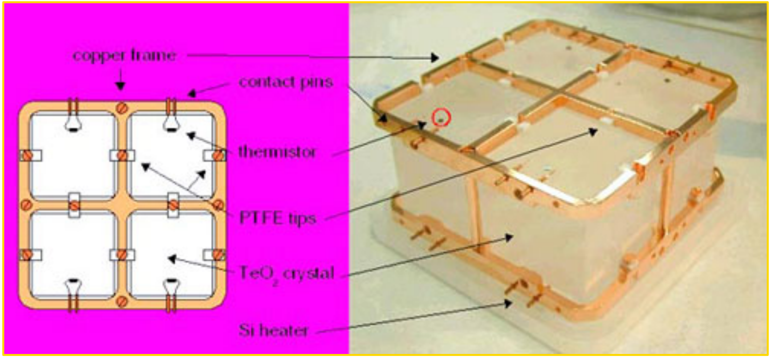


$T_{1/2} > 1.1 \times 10^{24}$ years

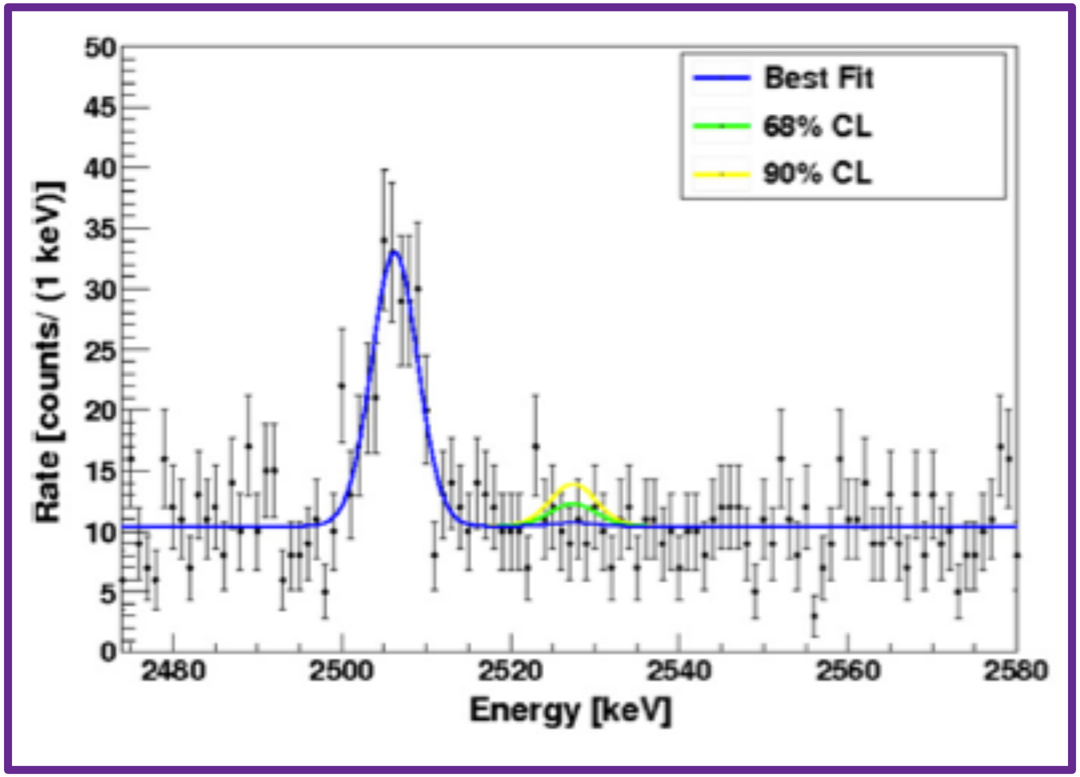
See S Blot's talk

CUORICINO

- ^{130}Te Bolometer



Astropart.Phys. 34, 822 (2011)



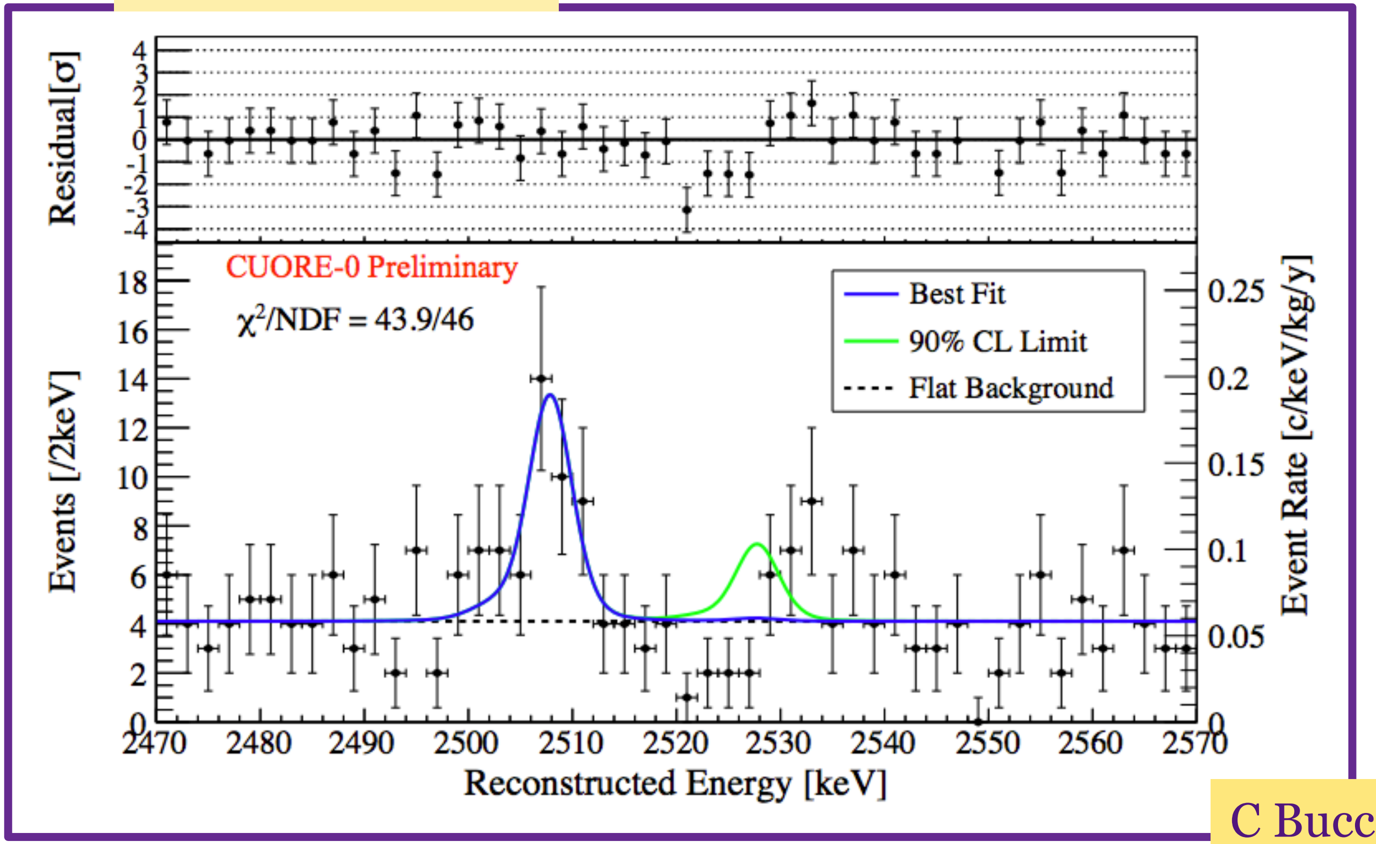
$T_{1/2} > 2.8 \times 10^{24}$ years

CUORE-0

- Next phase of CUORICINO technique

$T_{1/2} > 2.7 \times 10^{24}$ years

arXiv:1504.02454

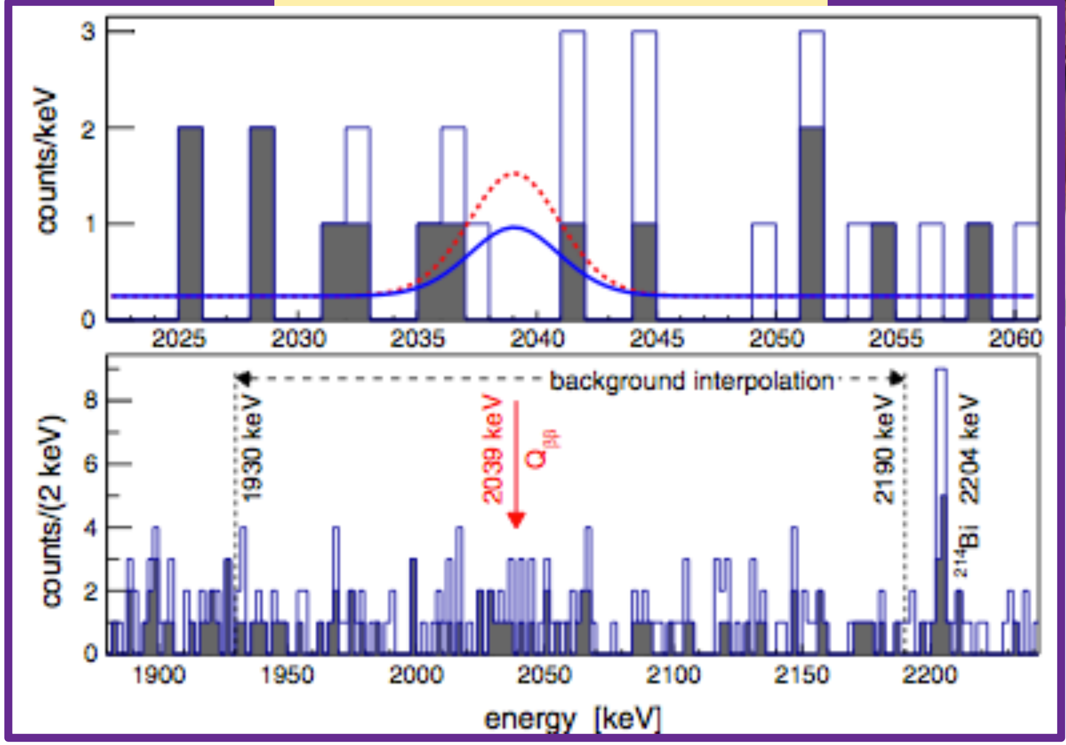


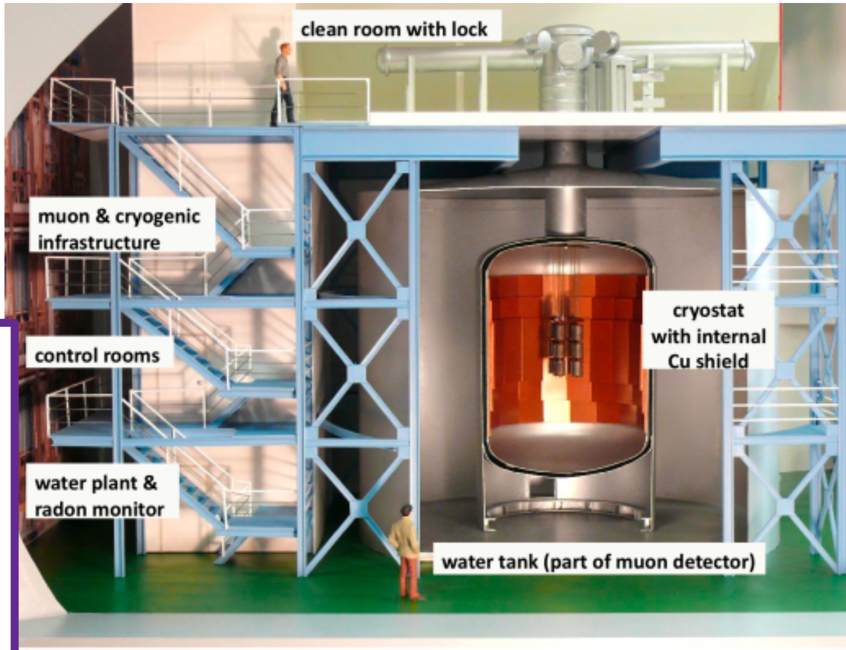
C Bucci's talk

GERDA

- Germanium crystal
  - ^{76}Ge isotope

PRL 111, 122503 (2013)





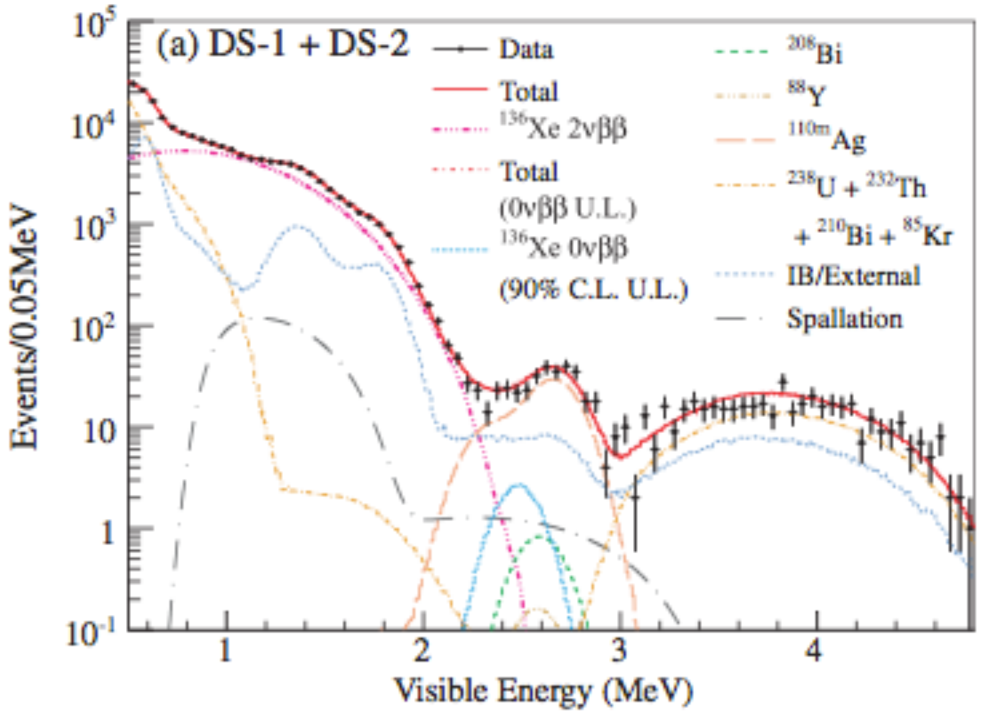
$T_{1/2} > 2.1 \times 10^{25}$ years

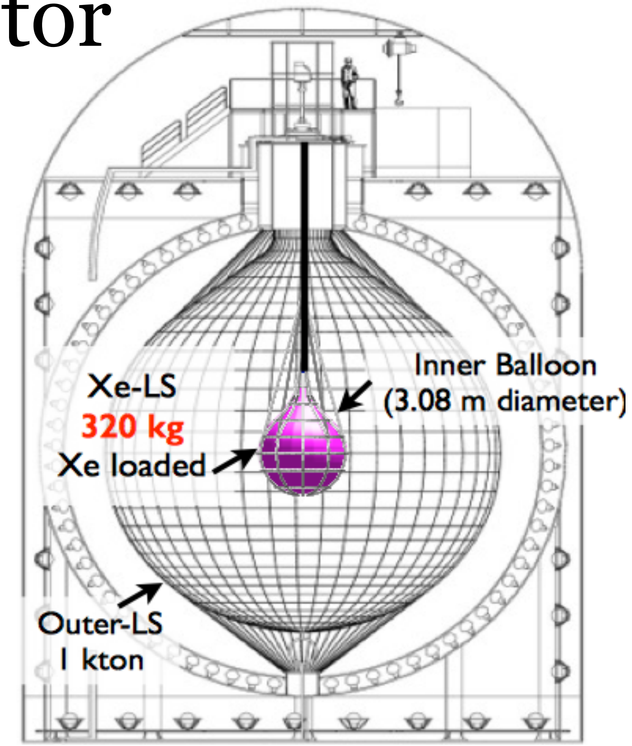
Talk by K Gusev

KamLAND-Zen

- Xenon-loaded liquid scintillator
  - ^{136}Xe isotope

PRL 110 062502 (2013)

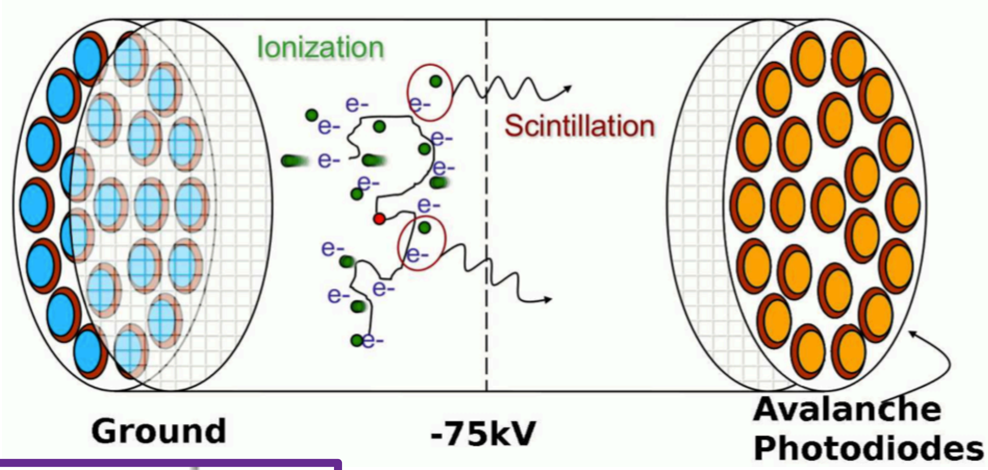




$T_{1/2} > 1.9 \times 10^{25}$ years

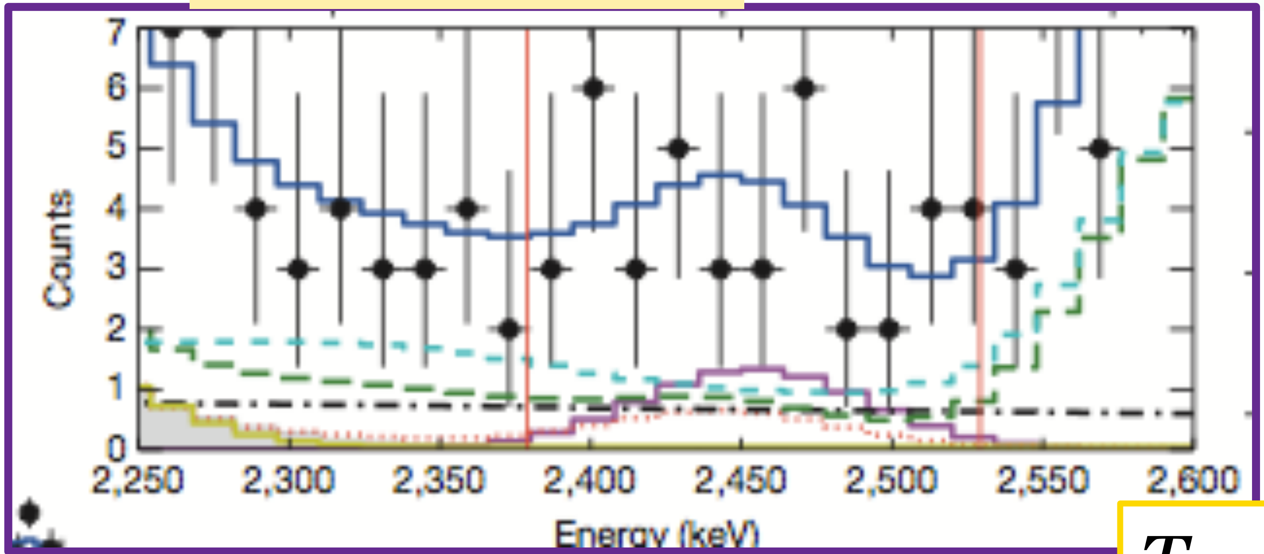
EXO-200

- Liquid xenon TPC
  - ^{136}Xe isotope



Talk by I Ostrovskiy

Nature 510, 229 (2014)



$T_{1/2} > 1.1 \times 10^{25}$ years

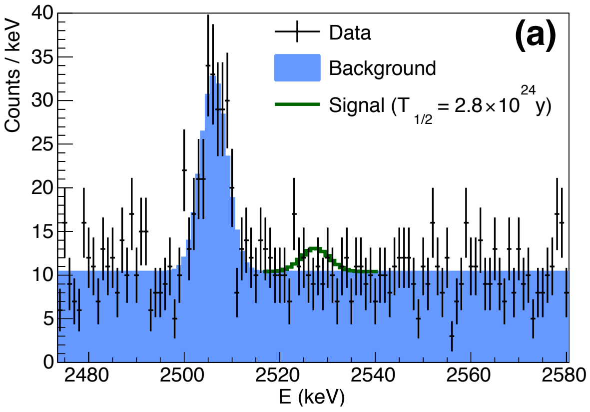
Summary of experiments

Experiment	Isotope	Method	Exposure (kg y)	$T_{1/2}$ 90% CL limit (years)	$m_{\beta\beta}$ limit (meV)
CUORICINO	^{130}Te	Bolometer	19.75	2.8×10^{24}	300 - 710
CUORE-0	^{130}Te	Bolometer	9.8	2.7×10^{24}	330 - 790
EXO-200	^{136}Xe	TPC	100	1.1×10^{25}	190 - 450
GERDA	^{76}Ge	Calorimeter	21.6	2.1×10^{25}	240 - 480
KamLAND-Zen	^{136}Xe	Loaded scintillator	89.5	1.9×10^{25}	160 - 330
NEMO-3	^{100}Mo	Foil-Tracker-Calorimeter	34.7	1.1×10^{24}	300 - 900

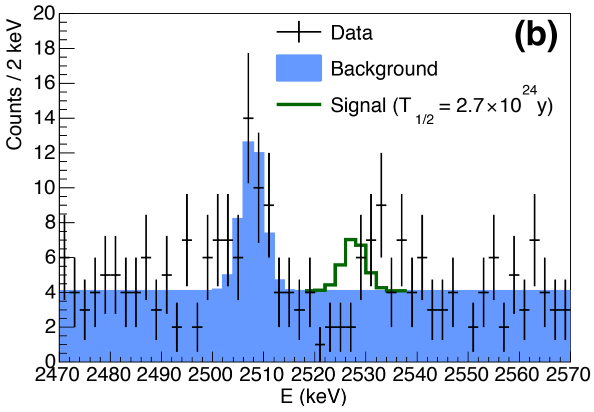
THE COMBINATION

The experimental data distributions

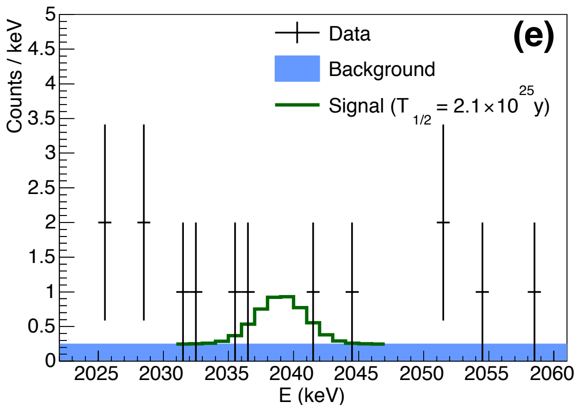
CUORICINO



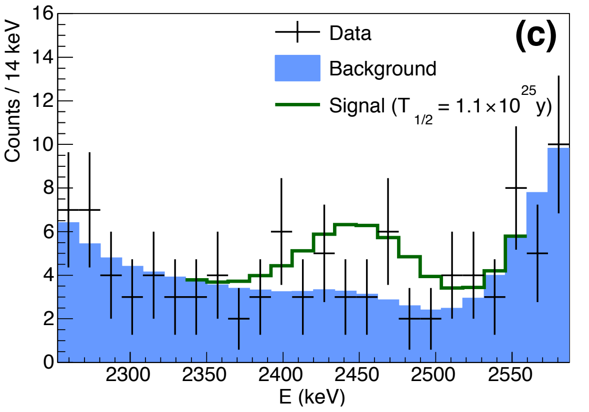
CUORE-0



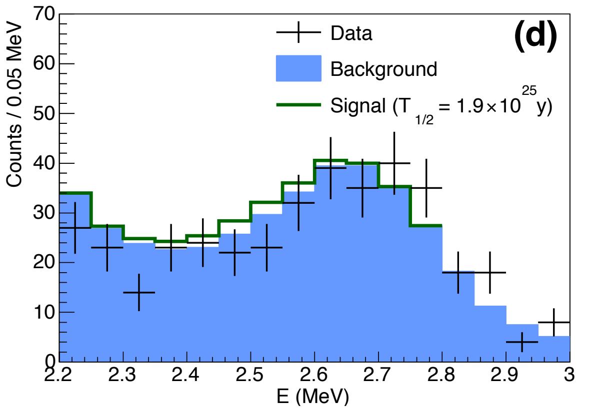
GERDA



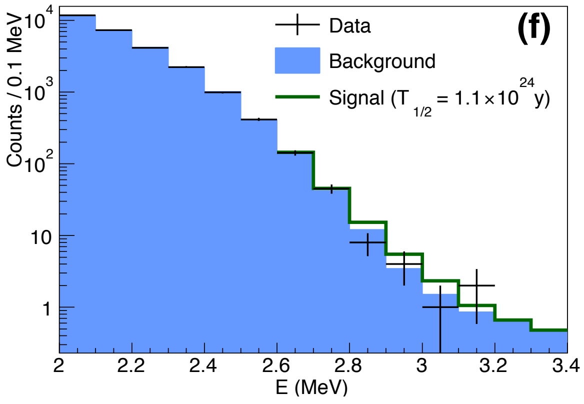
EXO



KamLAND-Zen

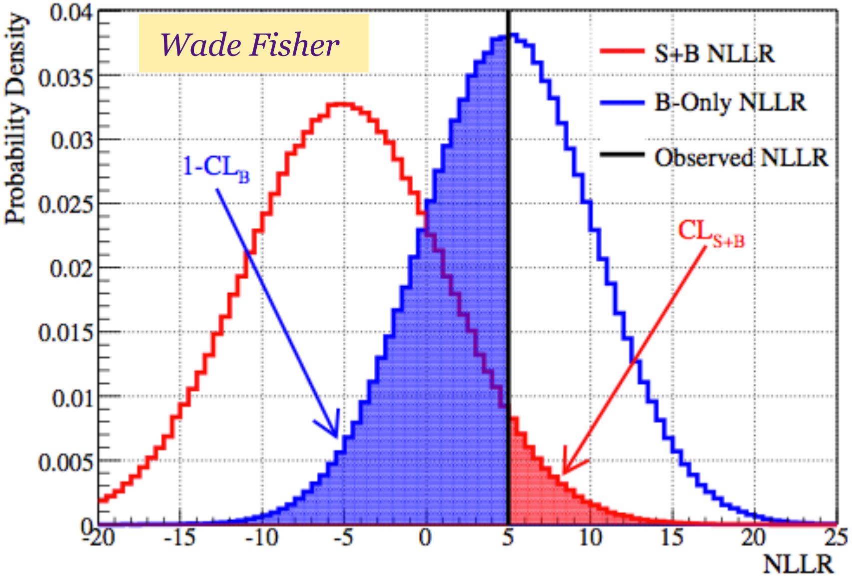


NEMO-3



Aside: CL_s limit setting method

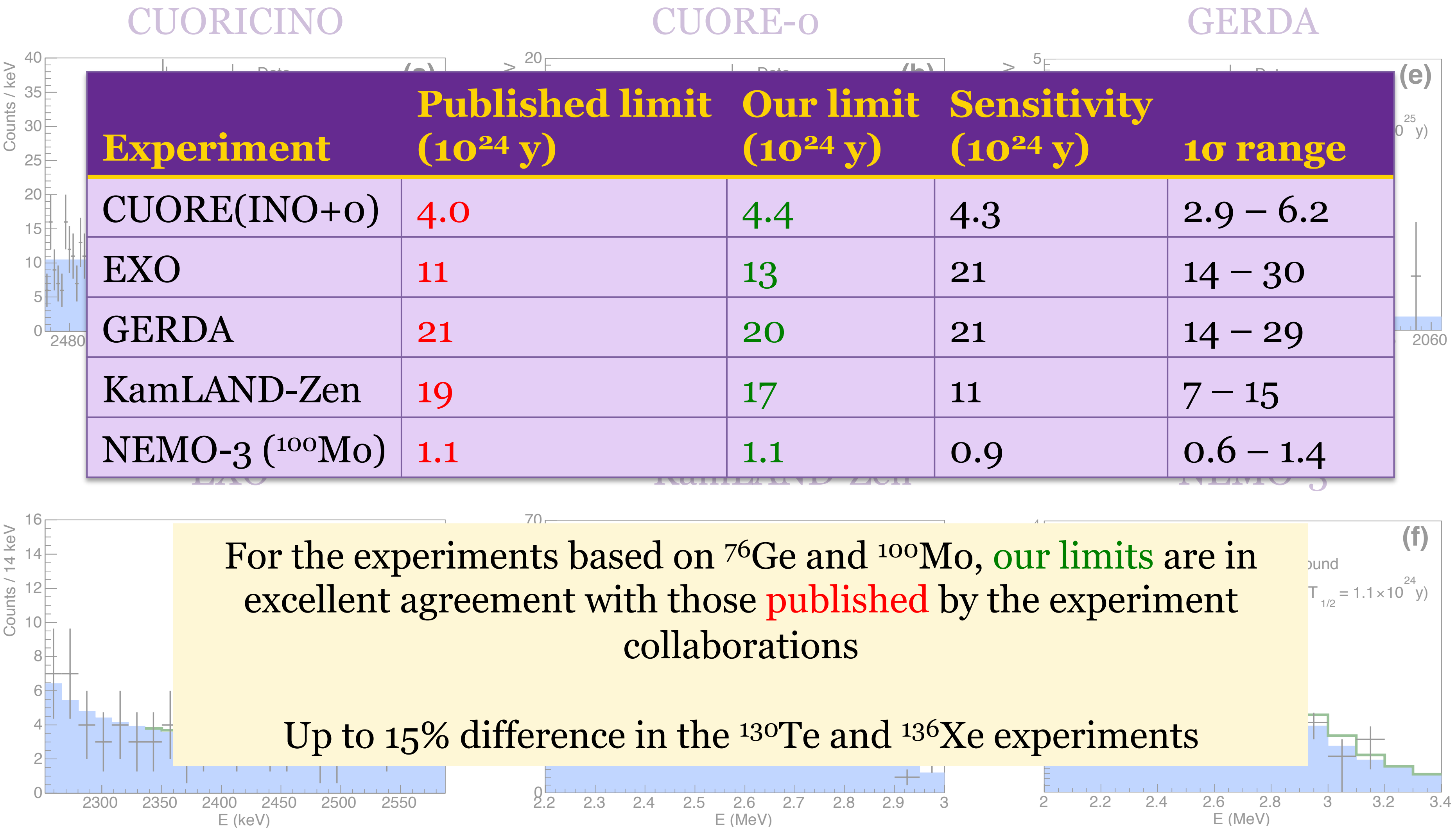
- For each experimental data distribution there are two models
  - Background only (B)
  - Signal + background (S+B)
  - Signal normalisation can be scaled
- Calculate the Log Likelihood Ratio (LLR) for the data in both hypotheses
- Adjust signal normalisation until CL_s = 0.1 (for 90% CL)



$CL_s = CL_{s+b} / CL_b$

CL_H is the p-value of the data LLR in the H hypothesis

Cross checks of experimental inputs



Experiment	Published limit (10^{24} y)	Our limit (10^{24} y)	Sensitivity (10^{24} y)	1σ range
CUORE(INO+0)	4.0	4.4	4.3	2.9 – 6.2
EXO	11	13	21	14 – 30
GERDA	21	20	21	14 – 29
KamLAND-Zen	19	17	11	7 – 15
NEMO-3 (^{100}Mo)	1.1	1.1	0.9	0.6 – 1.4

For the experiments based on ^{76}Ge and ^{100}Mo, our limits are in excellent agreement with those published by the experiment collaborations

Up to 15% difference in the ^{130}Te and ^{136}Xe experiments

Calculating half life

effective neutrino mass

Decay rate :-
signal
normalisation

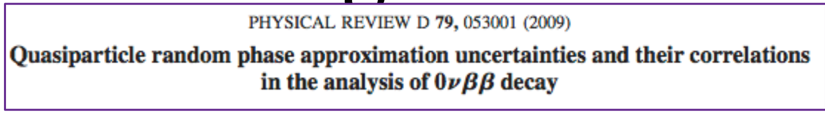
Phase space factor
(isotope-dependent)

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$

Nuclear matrix element
(isotope-dependent)

Nuclear Matrix Elements

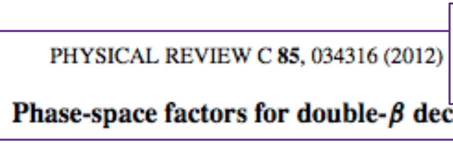
- Use phase space factors and NMEs to give you the relative normalisation of signals between experiments


PHYSICAL REVIEW D **79**, 053001 (2009)

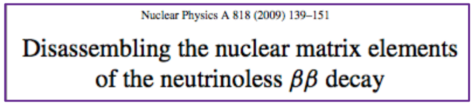
Quasiparticle random phase approximation uncertainties and their correlations in the analysis of $0\nu\beta\beta$ decay


PRL **105**, 252503 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

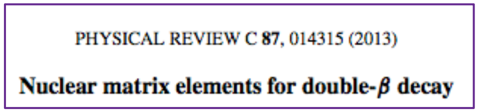
Energy Density Functional Study of Nuclear Matrix Elements for Neutrinoless $\beta\beta$ Decay


PHYSICAL REVIEW C **85**, 034316 (2012)

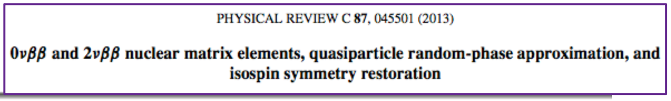
Phase-space factors for double-β decay


Nuclear Physics A 818 (2009) 139–151

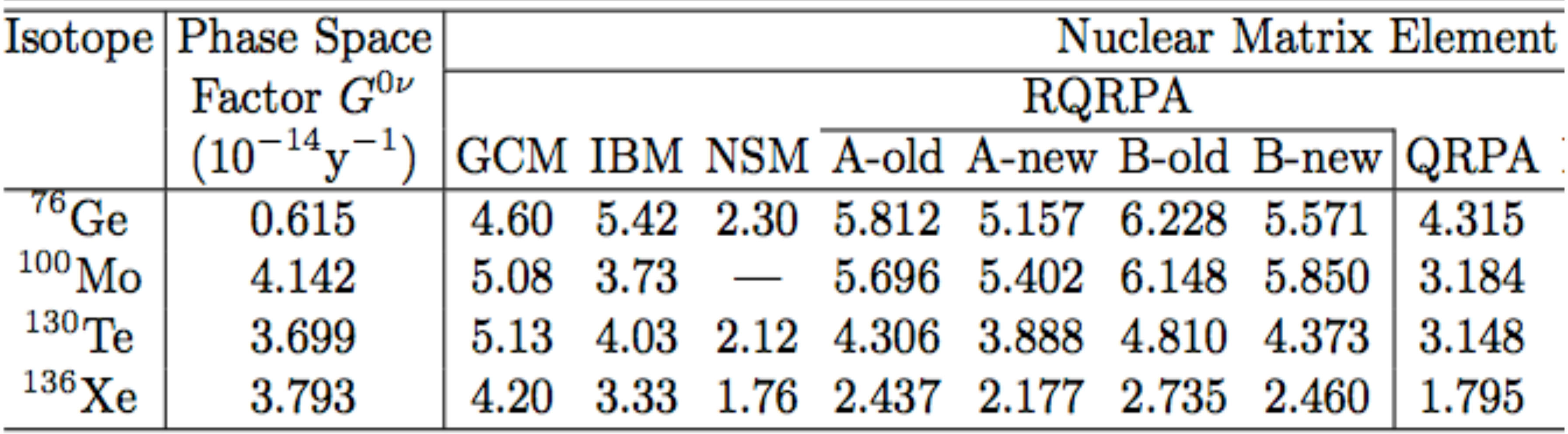
Disassembling the nuclear matrix elements of the neutrinoless $\beta\beta$ decay


PHYSICAL REVIEW C **87**, 014315 (2013)

Nuclear matrix elements for double-β decay

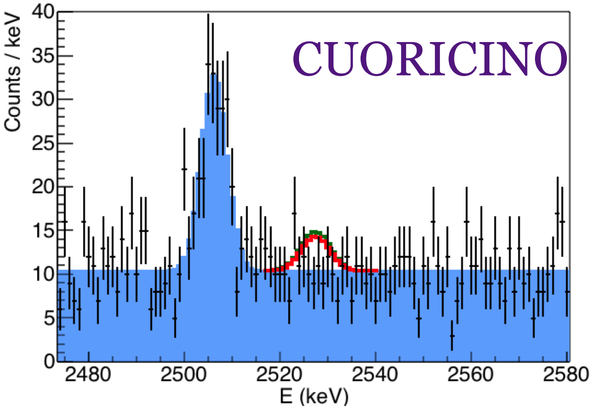

PHYSICAL REVIEW C **87**, 045501 (2013)

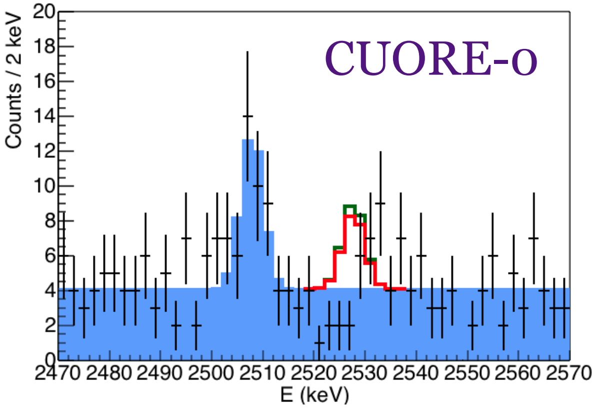
$0\nu\beta\beta$ and $2\nu\beta\beta$ nuclear matrix elements, quasiparticle random-phase approximation, and isospin symmetry restoration

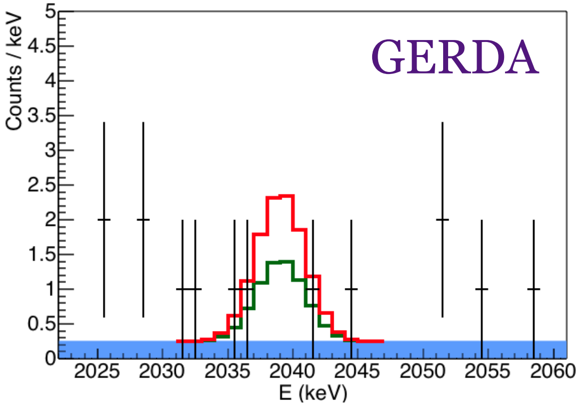


Isotope	Phase Space Factor $G^{0\nu}$ $(10^{-14}\mathrm{y}^{-1})$	Nuclear Matrix Element							
					RQRPA				
		GCM	IBM	NSM	A-old	A-new	B-old	B-new	QRPA
^{76}Ge	0.615	4.60	5.42	2.30	5.812	5.157	6.228	5.571	4.315
^{100}Mo	4.142	5.08	3.73	—	5.696	5.402	6.148	5.850	3.184
^{130}Te	3.699	5.13	4.03	2.12	4.306	3.888	4.810	4.373	3.148
^{136}Xe	3.793	4.20	3.33	1.76	2.437	2.177	2.735	2.460	1.795

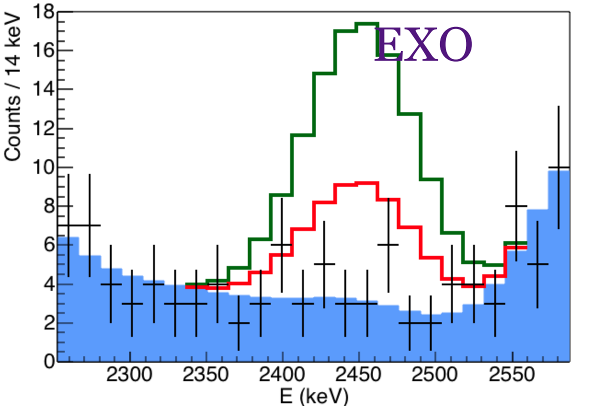
NME effects on signal rates

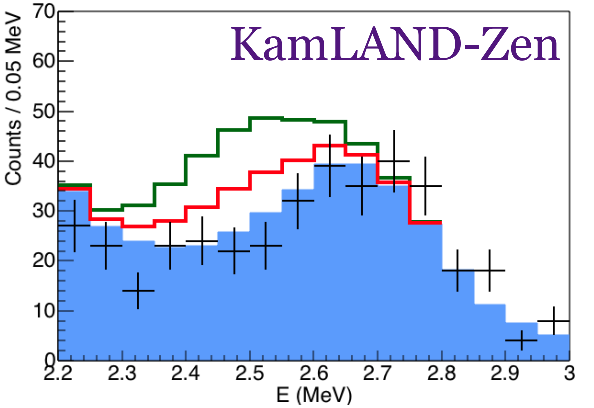


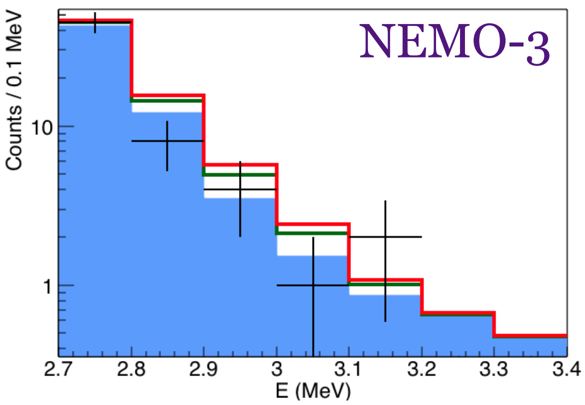




For the *GCM* or *QRPA* NMEs with $m_{\beta\beta}$ = 400 meV







NME effects on signal rates

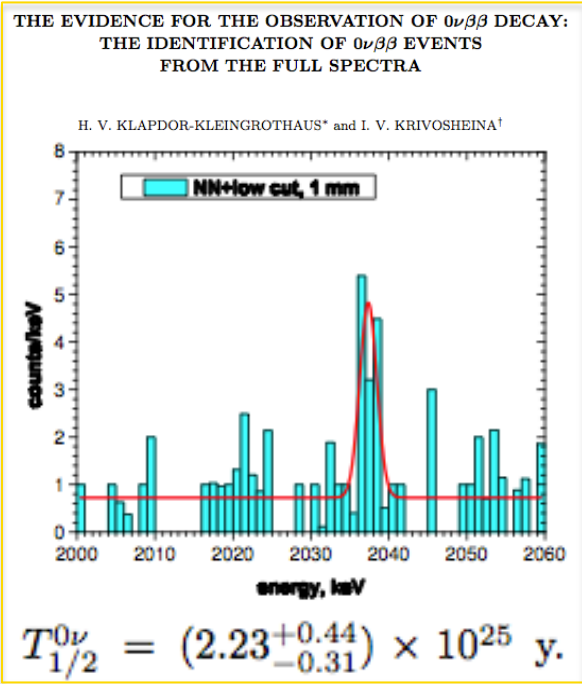
- For a constant $m_{\beta\beta}$, between two models:
  - For some isotopes (^{76}Ge, ^{100}Mo) the signal normalisation has increased
  - For other isotopes (^{130}Te, ^{136}Xe) the signal normalisation has decreased
  - Some isotopes have large change, some very similar
- We produce limits on $m_{\beta\beta}$ that depend on the NME
- The combined limit is made through summing the LLRs of the individual experiments in the CL_s method
  - signal normalisation depending on $m_{\beta\beta}$ as per the half-life formula

Results

(improvement wrt best individual experiment)

NME			limit (meV)	Improvement		HM *p*-value
				limit	sensitivity	
GCM [1]			130	12%	10%	0.0001
IBM [2]			190	16%	13%	0.021
NSM [3]			310	14%	10%	0.003
QRPA [4]	Argonne	new	200	23%	25%	0.095
		old	180	26%	25%	0.100
	Bonn	new	180	28%	24%	0.073
		old	170	28%	23%	0.077
pnQRPA [5]			170	19%	16%	0.029
(R)QRPA [6]			290	23%	21%	0.311

Heidelberg-Moscow experiment



THE EVIDENCE FOR THE OBSERVATION OF $0\nu\beta\beta$ DECAY: THE IDENTIFICATION OF $0\nu\beta\beta$ EVENTS FROM THE FULL SPECTRA

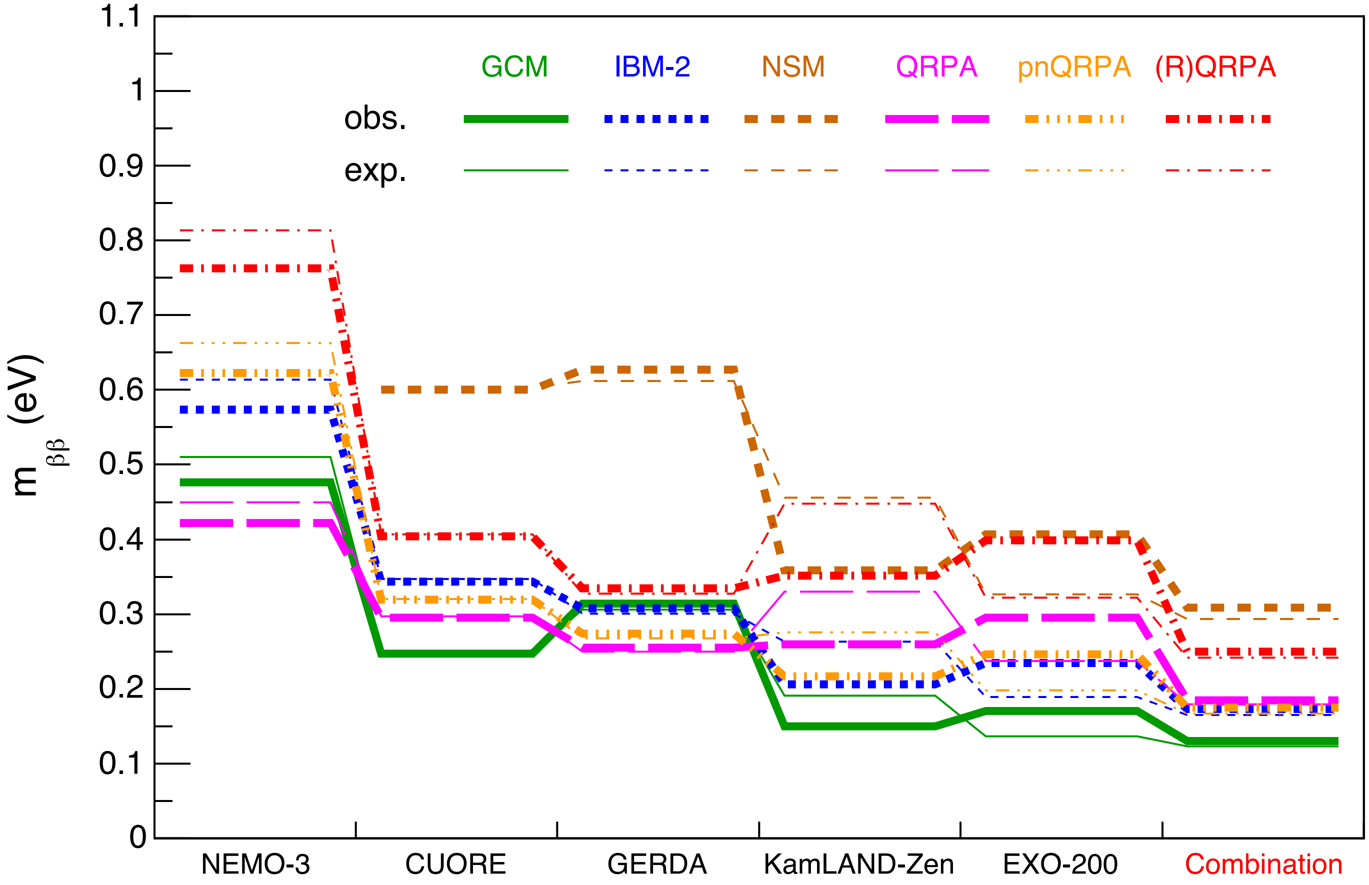
H. V. KLAPDOR-KLEINGROTHAUS* and I. V. KRIVOSHEINA†

$$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25} \text{ y.}$$

Mod Phys Lett A 21 1547 (2006)

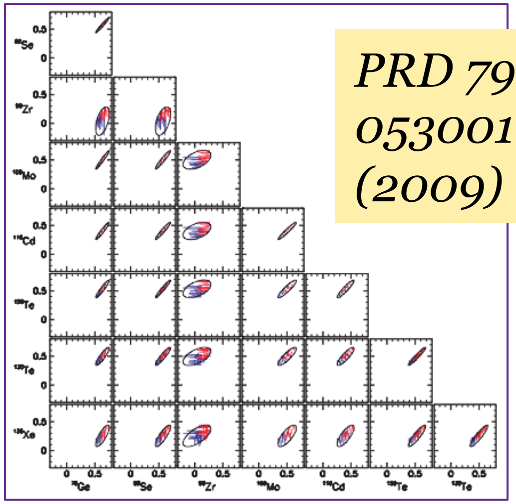
[1] PRL 105, 252503 (2010) *[2] PRC 91, 034304 (2015)* *[3] Nucl.Phys.A 818, 139 (2009)*
[4] PRC 87, 045501 (2013) *[5] PRC 91, 024613 (2015)* *[6] PRD 79, 053001 (2009)*

Results Graphically

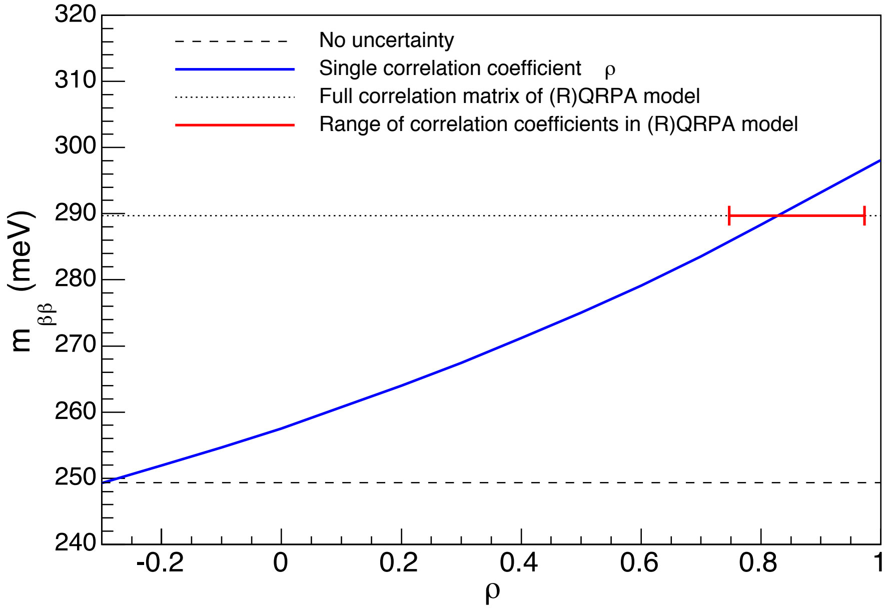


QRPA uncertainty & correlation

Isotope		Correlation Matrix			
	Rel. Unc.	^{76}Ge	^{100}Mo	^{130}Te	^{136}Xe
^{76}Ge	0.191	1			
^{100}Mo	0.254	0.973	1		
^{130}Te	0.247	0.899	0.862	1	
^{136}Xe	0.293	0.805	0.747	0.916	1

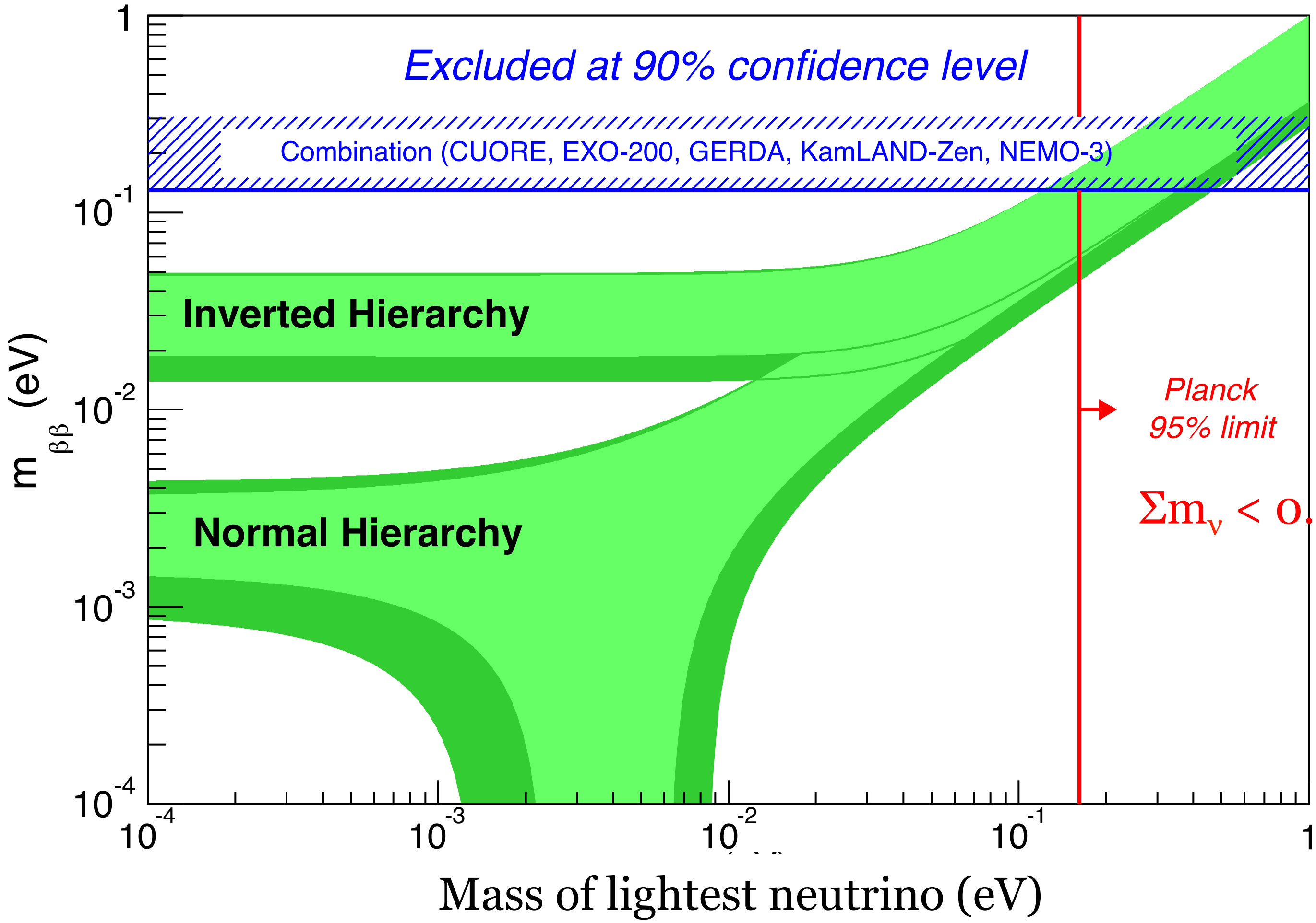


PRD 79, 053001 (2009)



- NME uncertainties lead to ~40-60% normalisation uncertainty on signal
- Effect of correlations can increase mass limit by up to 50 meV

The bigger picture



310 –
130 meV

$\Sigma m_\nu < 0.49$ eV

IMPLICATION FOR A STERILE MAJORANA NEUTRINO

How effective mass is calculated

$$m_{\beta\beta} = \Big| m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 e^{i\alpha} + \\ + m_3 \left|U_{e3}\right|^2 e^{i\beta} + m_4 \sin^2\theta_{14} e^{i\gamma} \Big|$$

3+1 sterile
neutrino model

Neutrino masses

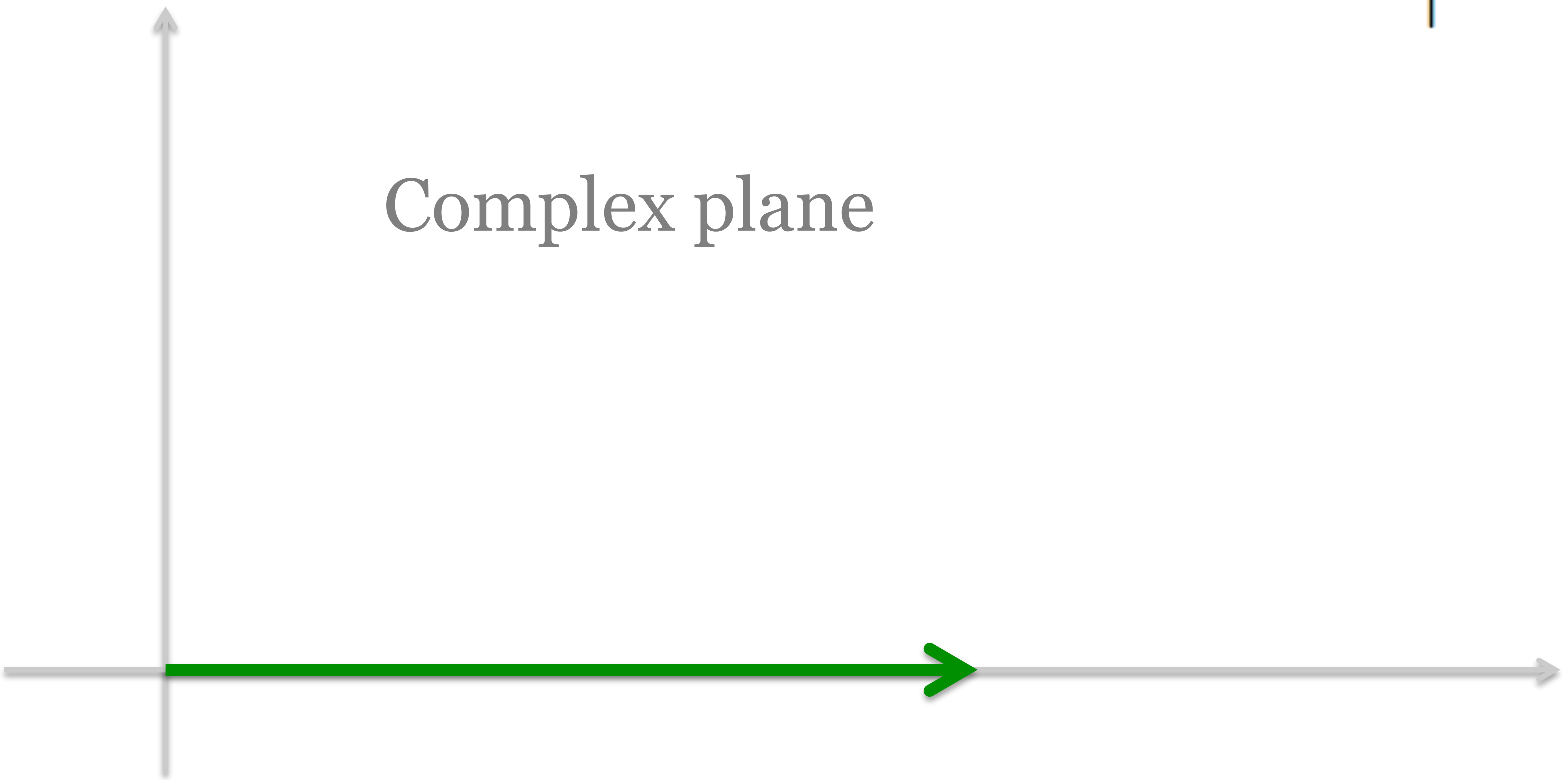
PMNS matrix elements

Majorana phases

Effective mass can be thought of as the length of the sum of vectors in the complex plane

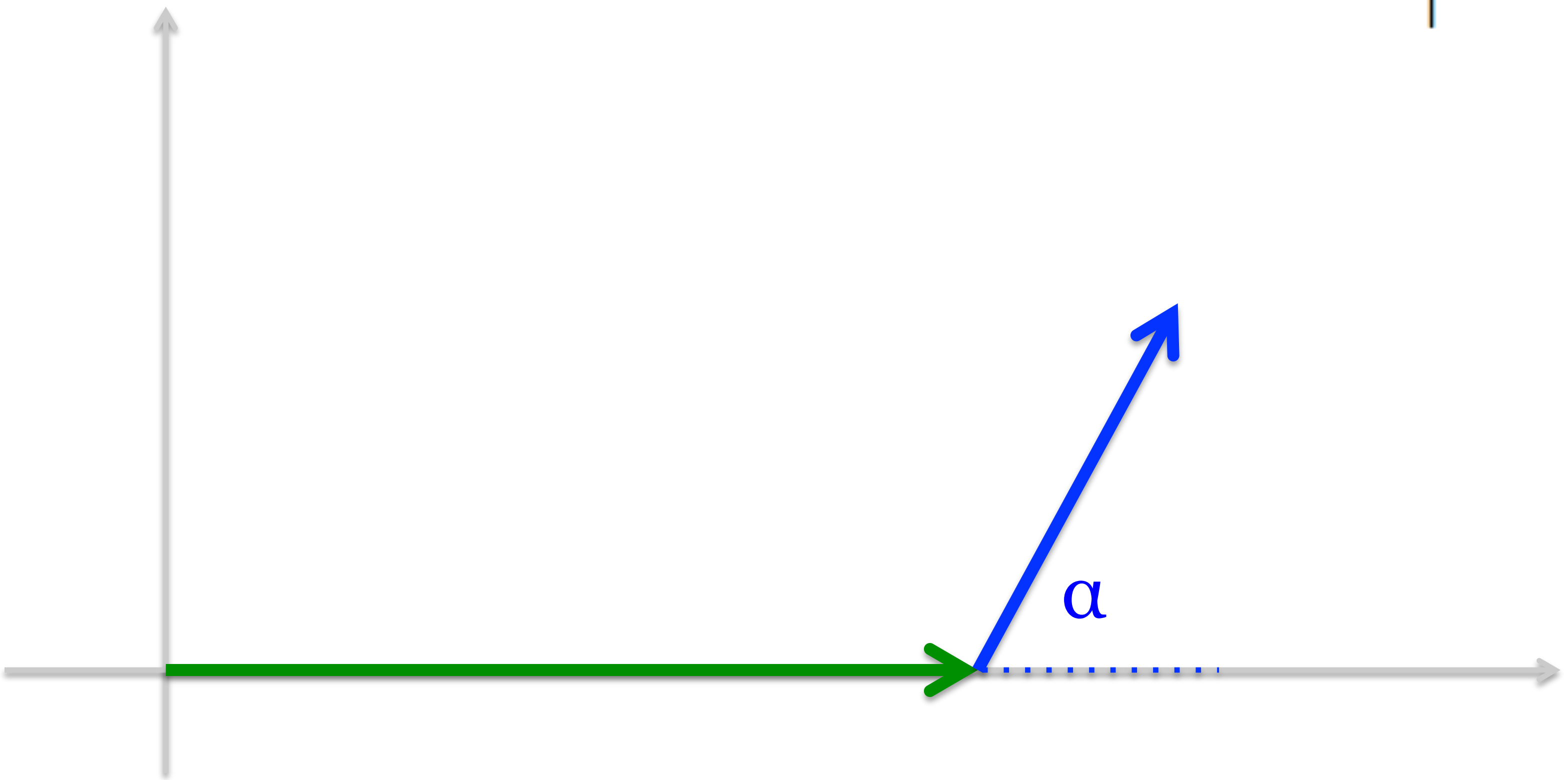
How effective mass is calculated

$$m_{\beta\beta} = \left| \underline{m_1 \left|U_{e1}\right|^2} + m_2 \left|U_{e2}\right|^2 e^{i\alpha} + \right.$$
$$\left. + m_3 \left|U_{e3}\right|^2 e^{i\beta} + m_4 \sin^2 \theta_{14} e^{i\gamma} \right|$$



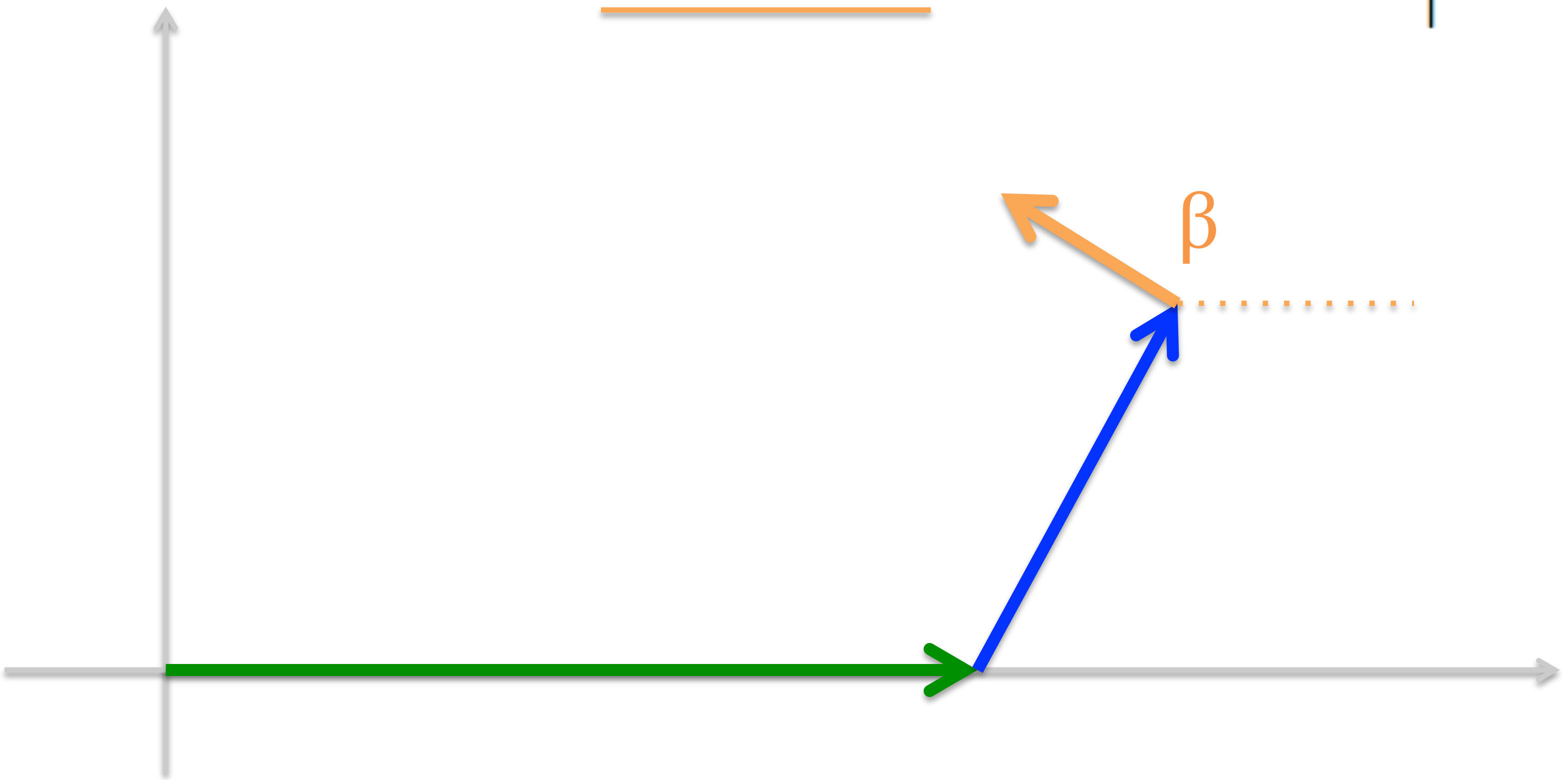
How effective mass is calculated

$$m_{\beta\beta} = \left| m_1 \left|U_{e1}\right|^2 + \underline{m_2 \left|U_{e2}\right|^2 e^{i\alpha}} + \right.$$
$$\left. + m_3 \left|U_{e3}\right|^2 e^{i\beta} + m_4 \sin^2\theta_{14} e^{i\gamma} \right|$$



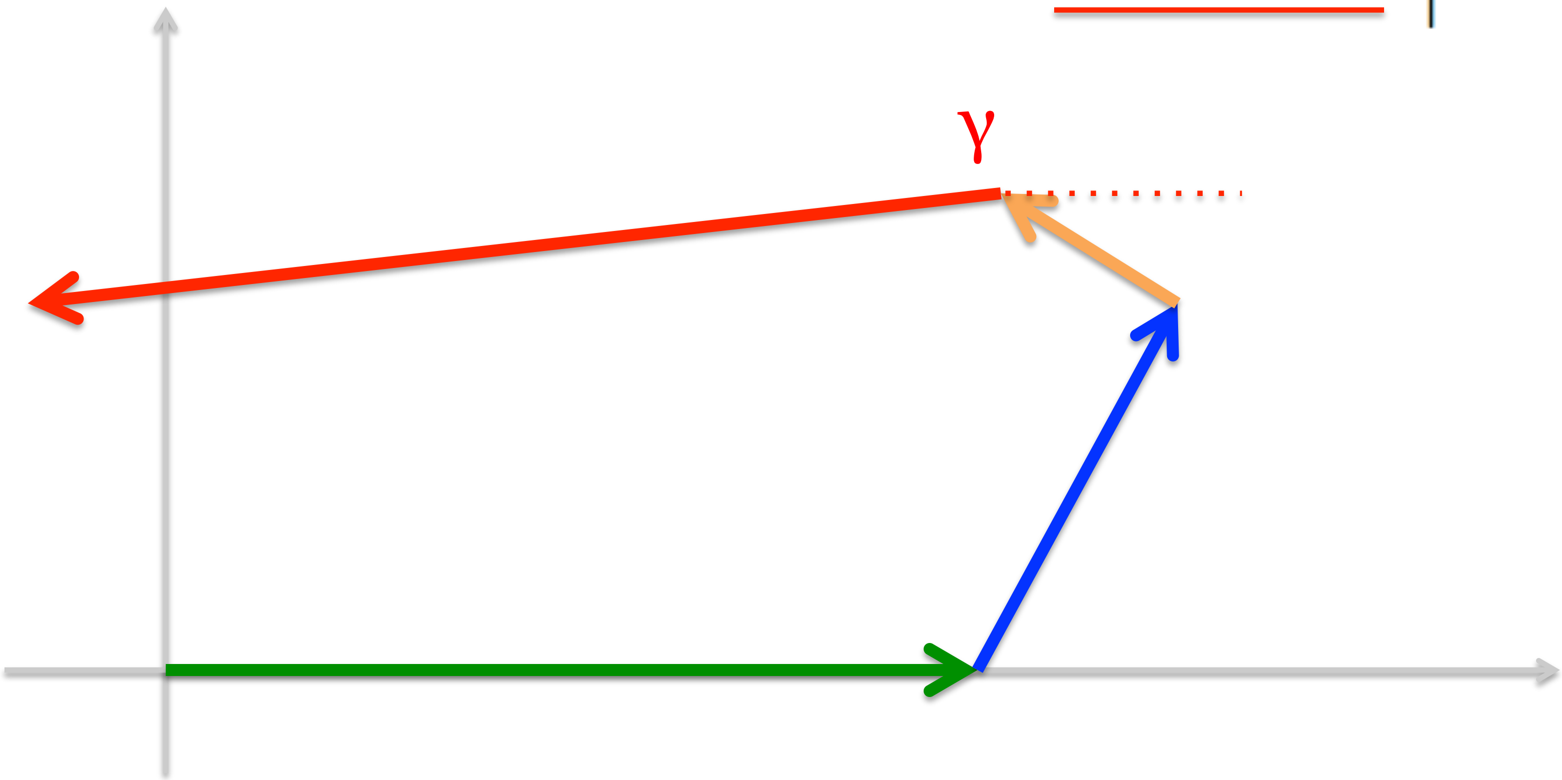
How effective mass is calculated

$$m_{\beta\beta} = \Big| m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 e^{i\alpha} + \\ + \underline{m_3 \left|U_{e3}\right|^2 e^{i\beta}} + m_4 \sin^2\theta_{14} e^{i\gamma} \Big|$$



How effective mass is calculated

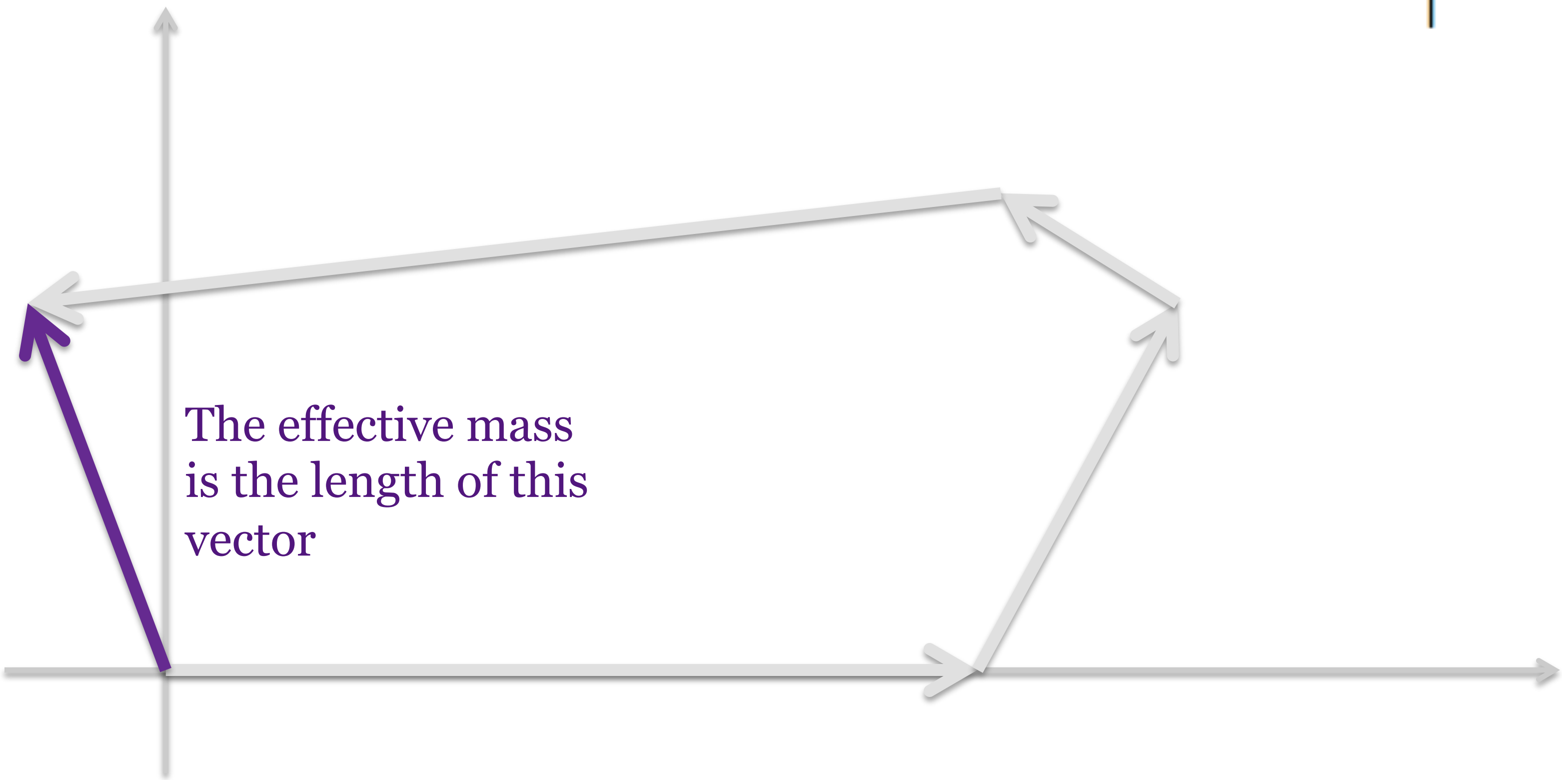
$$m_{\beta\beta} = \Big| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha} + $$
$$+ m_3 |U_{e3}|^2 e^{i\beta} + \underline{m_4 \sin^2\theta_{14} e^{i\gamma}} \Big|$$



How effective mass is calculated

$$\underline{m_{\beta\beta}} = \left| m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 e^{i\alpha} + \right.$$

$$\left. + m_3 \left|U_{e3}\right|^2 e^{i\beta} + m_4 \sin^2\theta_{14} e^{i\gamma} \right|$$



The effective mass is the length of this vector

Limits on sterile neutrino

$$m_{\beta\beta} = \left| \underline{m_1 \left|U_{e1}\right|^2} + \underline{m_2 \left|U_{e2}\right|^2 e^{i\alpha}} + \underline{m_3 \left|U_{e3}\right|^2 e^{i\beta}} + \underline{m_4 \sin^2\theta_{14} e^{i\gamma}} \right|$$

If we want to set limits on the sterile neutrino, we have two extreme cases:

$m_{\beta\beta}$ – the upper limit from our combination

if this line is shorter, $m_{\beta\beta}$ smaller than limit

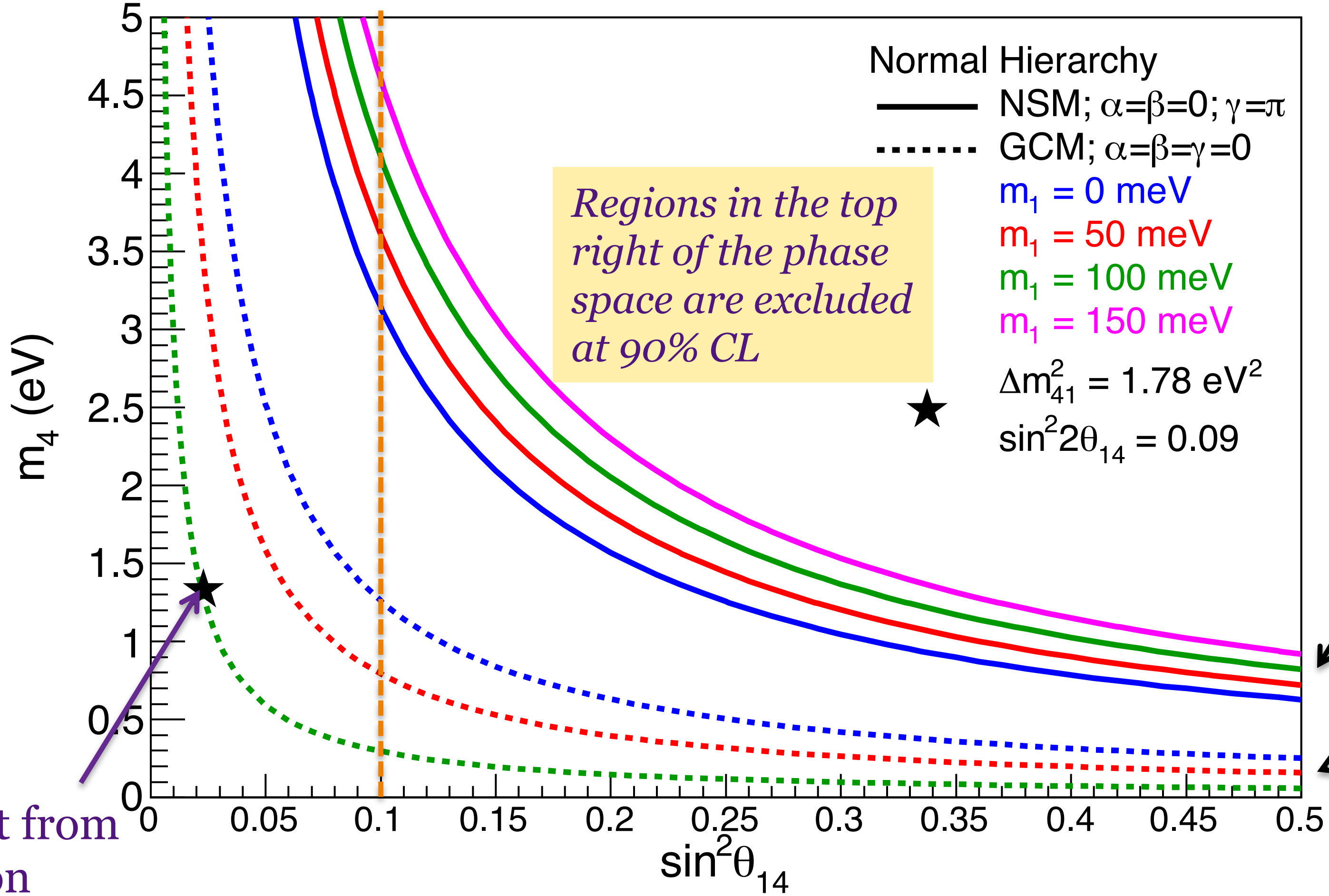
‘Best’ upper limit on m_4 for a **fixed $m_{\beta\beta}$** – all Majorana phases aligned

if this line is shorter, $m_{\beta\beta}$ smaller than limit

‘Worst’ upper limit on m_4 – ‘sterile’ Majorana phase antiparallel to active phases

Sterile Majorana neutrino limits

(approx limit from unitarity constraints in oscillation experiments)



Regions in the top right of the phase space are excluded at 90% CL

‘Worst’ limits

‘Best’ limits

Global fit from oscillation experiments
JHEP 05, 050 (2013)

SUMMARY

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- A first combination of 0νββ limits with multiple isotopes has been performed
  - $m_{\beta\beta} < 130 - 310$ meV (depending on NME)
- The combination can offer a sensitivity improvement equivalent to ~2x increase of exposure of the most sensitive individual experiment
- Limits can be set for a sterile Majorana neutrino, with the global best-fit candidate excluded in some favourable scenarios

- For more detailed information, please read

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